A BOTTOM GRAVITY SURVEY OF CARMEL BAY, CALIFORNIA

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THESIS

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by

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ABSTRACT

Bottom gravity data was obtained on 55 stations down to the 50 fathoms depth contour to produce the first gravity anomaly charts of Carmel Bay. The techniques of data collection and reduction are discussed. No evidence was found for the fault between Pescadero Point and Abalone Point proposed by Bowen. A layer of sediments over 500 meters thick, probably of the Paleocene Carmelo series, is indicated extending seaward from Carmel Beach, partially filling the secondary canyon. A new fault is proposed along the axis of the Carmel submarine canyon.

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LIST OF SYMBOLS AND ABBREVIATIONS

BC	-	Bouguer correction
CBA	-	complete Bouguer anomaly
CC	-	curvature correction
D_a	-	depth below mean sea level
D_o	-	measured depth
FAA	-	free air anomaly
FAC	-	free air correction
G	-	universal gravitational constant
L	-	latitude
OG	-	observed gravity
ρ_r	-	density of rock
ρ_w	-	density of water
SBA	-	simple Bouguer anomaly
TC	-	terrain correction
TD	-	tide height
THG	-	theoretical gravity

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I. INTRODUCTION

A. OBJECTIVE

The objective of this work was to produce, from a bottom gravity survey, gravity anomaly charts of Carmel Bay, and, in conjunction with other geological and seismic work, infer the substructure of the bay. This gravity survey is a complement to the ongoing study of the marine geology of Carmel Bay.

B. DESCRIPTION OF AREA

Carmel Bay is located approximately 5 miles south of Monterey Bay, California (Fig. 1). The main community on the bay is the village of Carmel. The bay is quite small, measuring about 3.5 by 1.5 miles, being limited on the north by Cypress Point and on the south by Point Lobos. Bottom topography is very irregular. Bottom composition varies from very fine muddy sediment to granite outcrops. Part of the bay is covered with kelp beds.

C. PREVIOUS INVESTIGATIONS

No previous gravimetric work has been done in Carmel Bay. Its geology has been studied for more than a century. J. B. Trask (1854, 1855) was one of the first geologists to study the region. The first extensive survey was made by Lawson (1893). More recently Bowen (1965) and Nili-Esfahani (1965) made studies of the region, and Simpson (1972) presented the latest geological study including the underwater structures and stratigraphy.

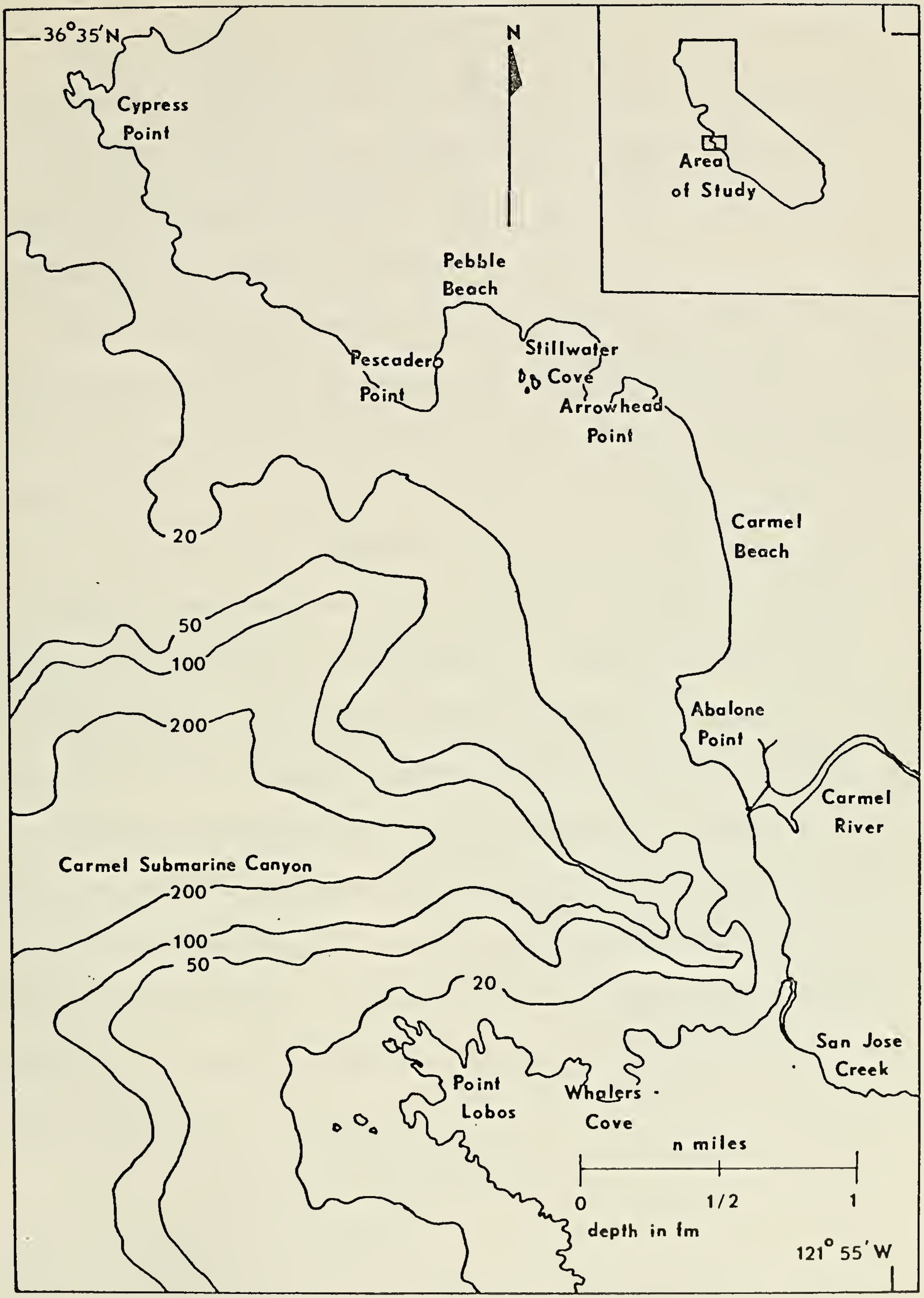

Figure 1. Location Map of Carmel Bay

The environment and origin of submarine canyons, with application to the Carmel Submarine Canyon, has been investigated by Shepard and Emery (1941), Shepard and Dill (1966), Martin (1964) and Martin and Emery (1967). Zardeskas (1971) studied the bathymetry of Carmel Bay and constructed a very accurate chart of the bottom.

Figure 2 depicts the geology of the bay according to Simpson (1972). Six rock types outcrop in the vicinity of Carmel Bay. A basement granodiorite intruded into the Paleozoic Sur Series during the Cretaceous period is the oldest. After erosion removed the Sur Series, the Paleocene Carmelo Formation was deposited as a turbidite in an environment similar to that of the Carmel Submarine Canyon today. Alternating periods of uplift and erosion resulted in the deposits of Temblor Sandstones and Monterey shales in the Middle and Upper Miocene. An iddingsite andesite lava flow separated these two Miocene deposits. The deep Carmel Submarine Canyon and numerous elevated and submerged terraces show the effects of changing sea levels during the Pleistocene ice ages. Another Pleistocene feature is a sediment deposit correlated with the Aromas Red Sandstones. A large granite pluton, upon which all younger rocks sit, has been the predominant feature of the area since the Cretaceous period.

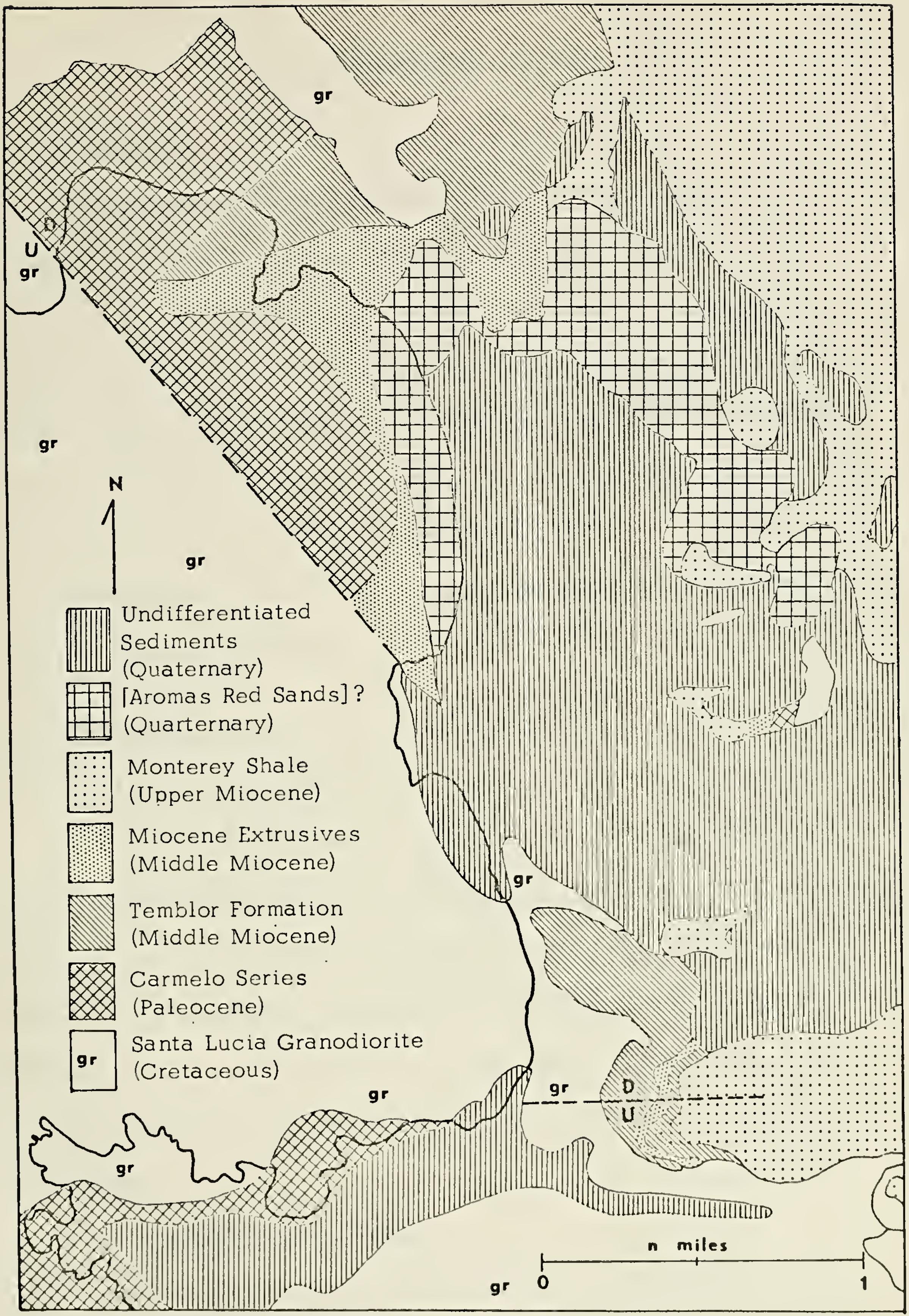

Figure 2. Geologic Map of Carmel Bay.

II. COLLECTION OF DATA

A. PLANNING

The planning of the survey was such as to cover the bay, from Cypress Point to Point Lobos, down to the 50 fathoms depth contour. To accomplish this, 70 gravity stations were planned, with a mean distance between stations of 0.25 miles. Due to the irregularity of the bottom contours the grid was not made regular but planned in a way to provide maximum coverage of the area. Due to problems mentioned later, gravity was only measured at 55 stations.

Also planned were six stations along the shoreline to provide a tie with existing inshore surveys.

B. EQUIPMENT

1. Land Gravity Meter

For the shoreline survey, the LaCoste & Romberg G17B land gravity meter was provided by the United States Geological Survey (USGS). This instrument works on the principle of the LaCoste seismograph. Figure 3 shows a simplified diagram of the meter. The meter has a worldwide range and an accuracy of ± 0.01 mgal. This instrument was also used to standardize the underwater gravity meter before shipboard installation.

2. Underwater Gravity Meter

For the main survey a LaCoste & Romberg Model H6G underwater gravity meter was provided by the Naval Oceanographic Office.

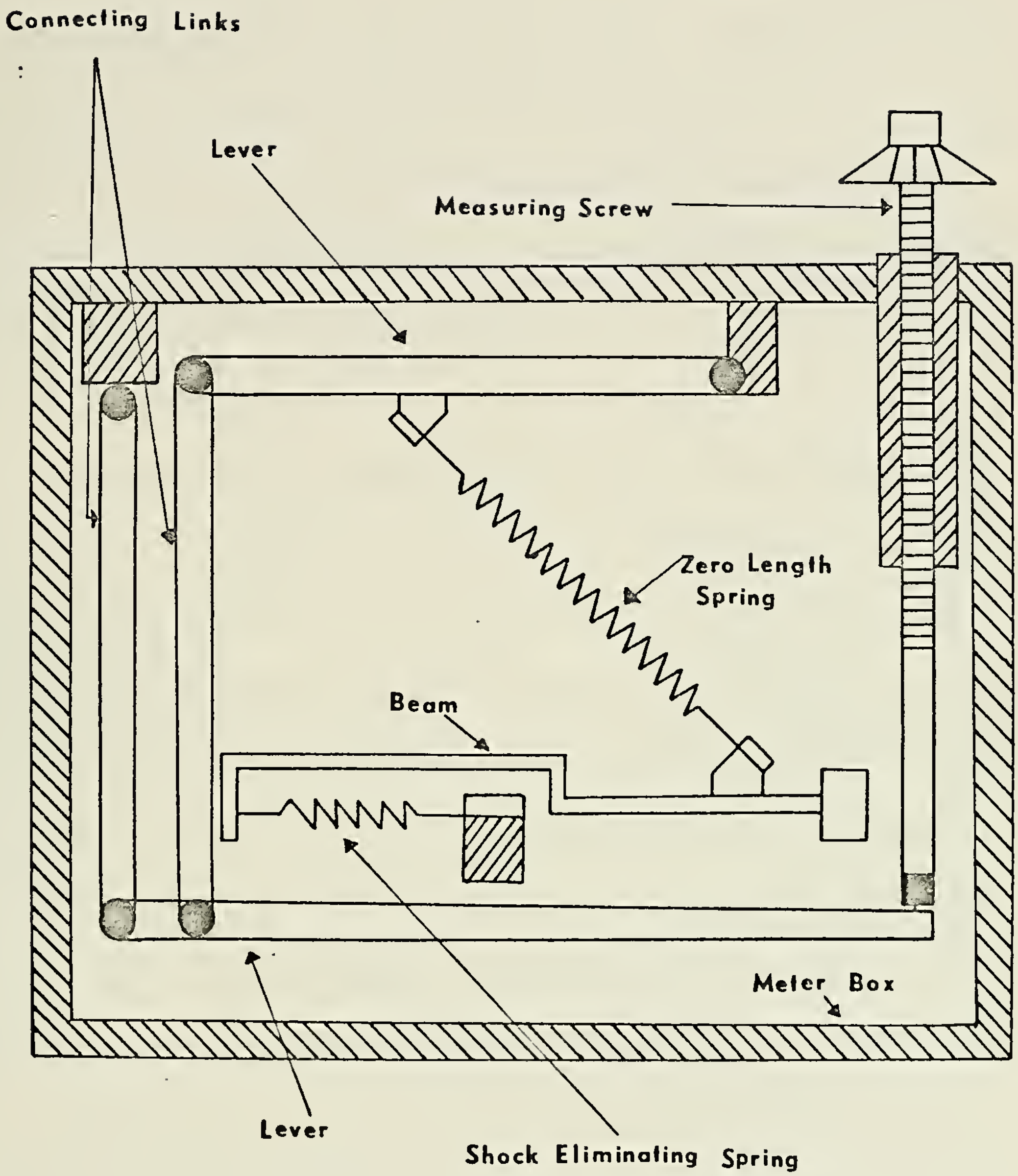

Figure 3. Simplified Diagram of the LaCoste & Romberg Gravity Meter

This instrument works also on the principle of the LaCoste seismograph and is similar to the land gravity meter mentioned above except for the watertight enclosure and a fully remote control system. This meter has worldwide range and an accuracy of ± 0.1 mgal. The leveling mechanism is automatic and works in the range of $\pm 15^{\circ}$ inclination.

Plate 1 shows the complete underwater unit with the electrical termination, and in Plate 2 the top part has been removed to show the actual gravity meter and electrical gear.

3. Shipboard Installation

The vessel R/V Acania used for the bay survey is the 126 ft oceanographic research vessel of the Naval Postgraduate School (NPS). The underwater gravity meter was installed on the survey ship with all the ancillary equipment as shown in Figure 4. An hydraulic winch was used to lower and raise the underwater unit through an 'A' frame, also hydraulically operated. Hydraulic power was provided by an hydraulic pump coupled to a gasoline engine. All this equipment was installed on the upper deck of the R/V Acania. The control unit was mounted on the main deck and used the ship's electrical supply through a Kepco power unit. Electrical power to the underwater unit was provided from the control unit through a slip ring assembly on the winch, winch cable and a watertight termination on the unit.

Plate 3 shows a view of the layout on the upper deck of the R/V Acania.

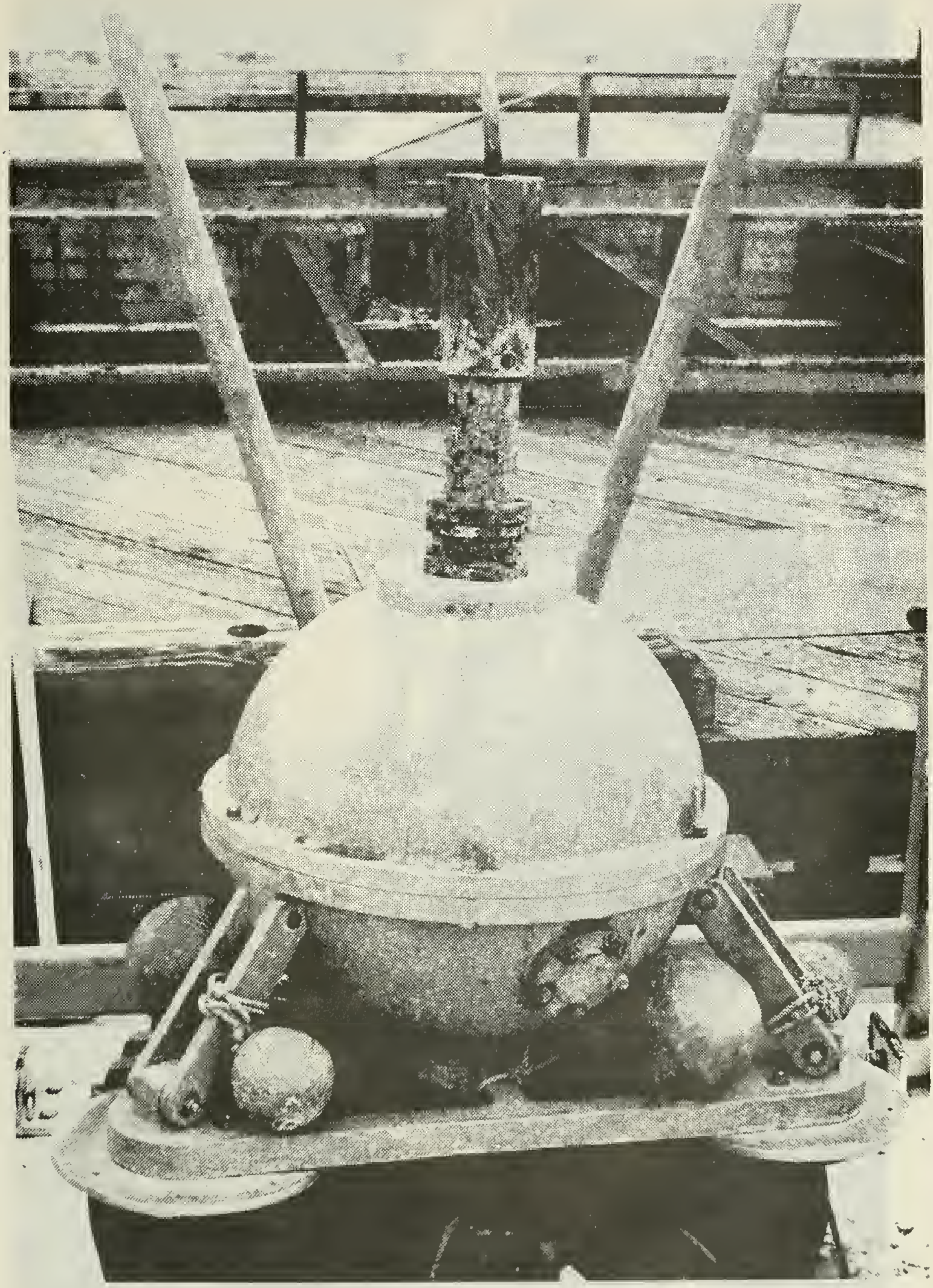

Plate 1. External View of Underwater Gravimeter, LaCoste & Romberg Model H6G.

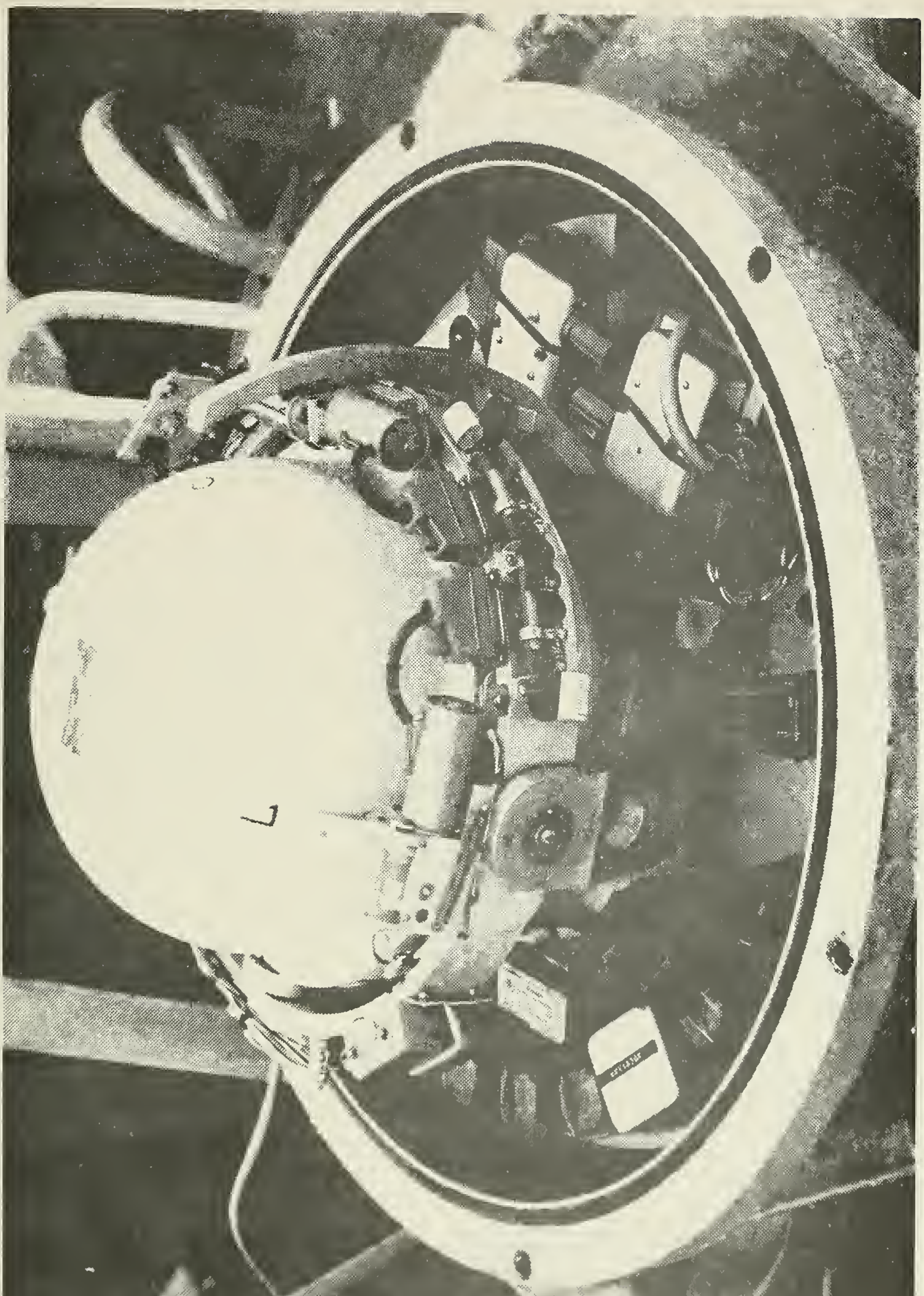

Plate 2. Underwater Gravimeter with Top Removed.

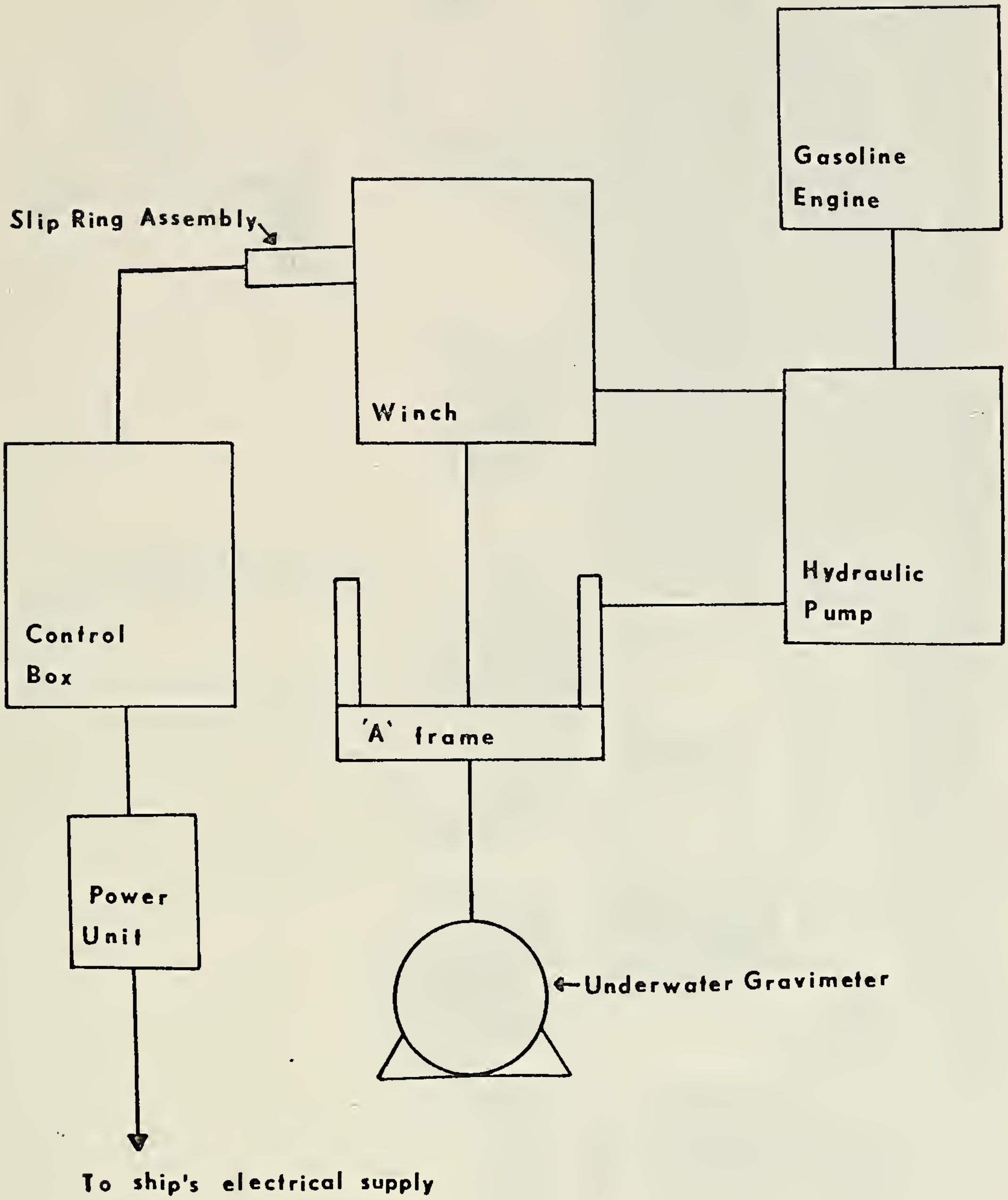

Figure 4. Schematic Diagram of the Complete Bottom Gravimeter Installation

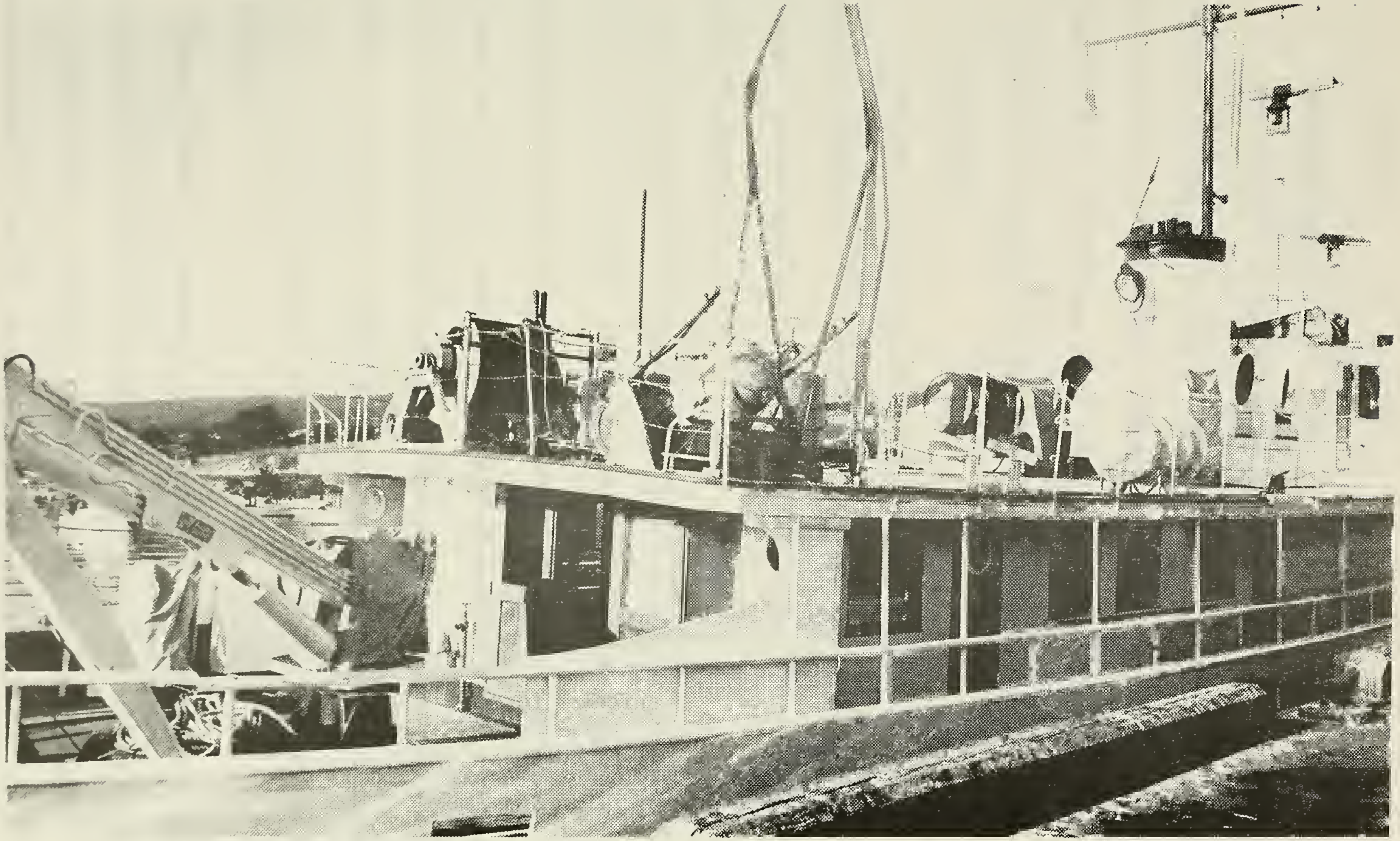

Plate 3. Equipment Layout on the Top Deck of the R/V _Acania_.

C. THE SURVEYS

1. Shoreline Survey

The shoreline survey was conducted on 27 April 1972 with the LaCoste & Romberg G17B meter. A total of six stations were occupied: Cypress Point, Stillwater Cove, Jeffreys Bench Mark at Abalone Point, Monastery Beach at San Jose Creek, Whalers Cove and Point Lobos.

Table I is a listing of the data obtained.

2. Bay Survey

The bay survey was completed in three days, on 18 and 19 August and 3 October 1972. The navigation fixes to determine the location of the stations were made by visual bearings and radar distances. Accuracy is estimated at 50 ft.

The rocky bottom and the kelp beds in part of the bay posed serious problems during the survey. Plate 4 shows the underwater unit after a station made over a kelp bed. Many planned stations could not be occupied and in some cases 20 lowerings and raisings of the underwater unit had to be made before finding a bottom slope with less than the allowed 15° inclination. These problems, along with electrical failures and the time available, made it possible to measure the gravity at only 55 stations.

Figure 5 shows the geographical location of the stations, the latitude and longitude for which are tabulated in Table II. Table III is a summary of the observed data. The depth indicated is the one obtained by the pressure sensor in the underwater unit.

TABLE I

SHORELINE STATIONS DATA

Station	Date	Hour (PST)	Elevation (ft)	Observed gravity (mgal)
Cypress Point	27 Apr 72	1239	14	979 906.01
Stillwater Cove	"	1206	14	979 902.84
Jeffreys B. M.	"	1338	30	979 902.76
Mission Beach	"	1400	5	979 902.31
Whaler's Cove	"	1419	3	979 904.12
Point Lobos	"	1435	5	979 904.41

Station	Latitude N	Longitude W
Cypress Point	36° 34'.26	121° 58'.35
Stillwater Cove	36 33.98	121 56.52
Jeffreys B. M.	36 32.61	121 55.93
Mission Beach	36 31.52	121 55.42
Whaler's Cove	36 31.19	121 56.36
Point Lobos	36 31.13	121 57.15

Station	Theoretical gravity 1930 formula (mgal)	Theoretical gravity 1967 formula (mgal)	CBA 1930 (mgal)	CBA 1967 (mgal)
Cypress Point	979 879.91	979 866.42	26.10	39.60
Stillwater Cove	979 879.48	979 865.99	23.36	38.86
Jeffreys B. M.	979 877.52	979 864.03	25.24	38.74
Mission Beach	979 875.96	979 862.46	26.35	39.85
Whaler's Cove	979 875.48	979 861.98	28.64	42.14
Point Lobos	979 875.39	979 861.89	29.02	42.52

Plate 4. Underwater Unit after a Station over a Kelp Bed.

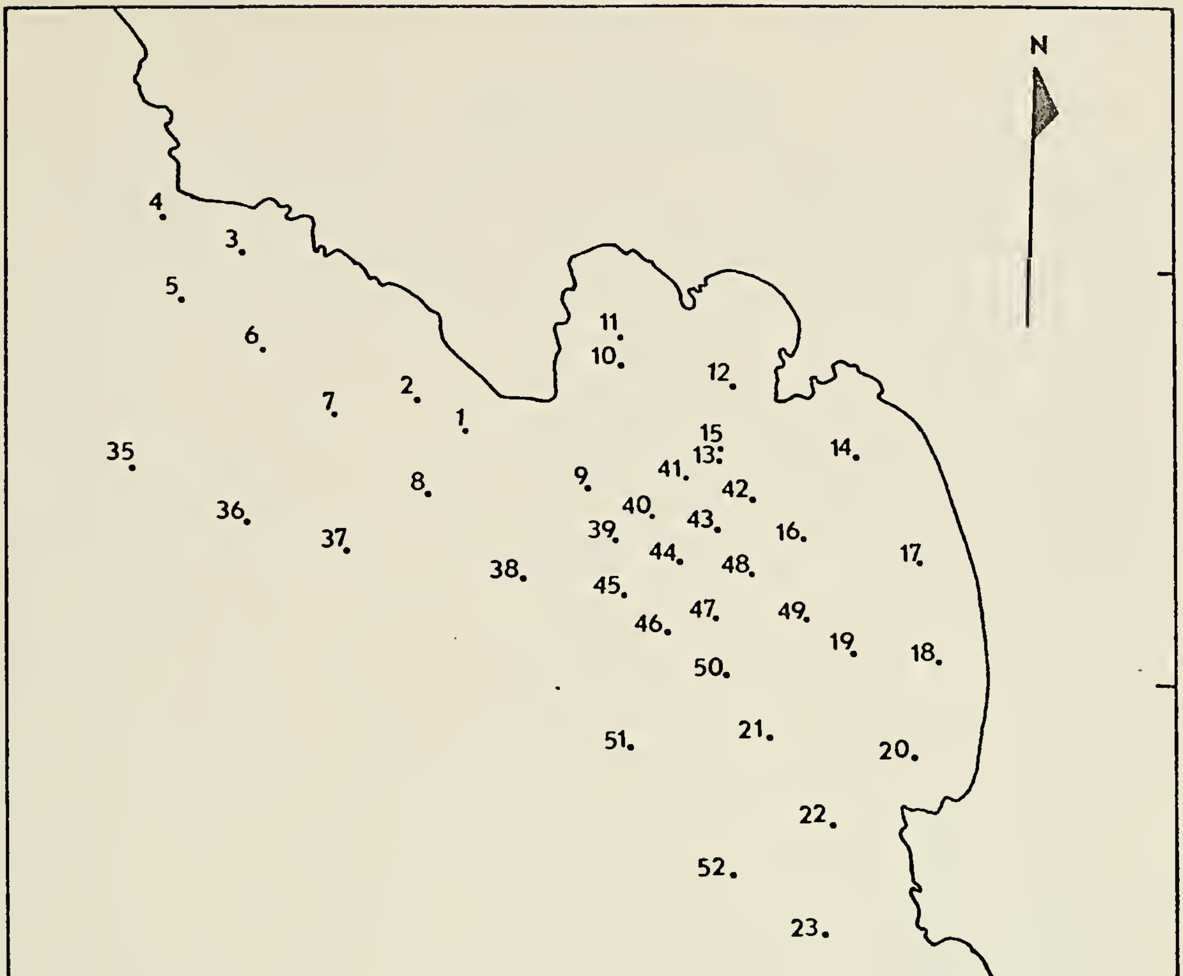

Figure 5. Station Location for Underwater Stations

TABLE II

STATION LOCATION

Station	Latitude N	Longitude W
1	36° 33'.58	121° 57'.29
2	36 33.66	121 57.45
3	36 34.02	121 58.01
4	36 34.11	121 58.28
5	36 33.90	121 58.19
6	36 33.78	121 57.93
7	36 33.62	121 57.70
8	36 33.42	121 57.41
9	36 33.44	121 56.93
10	36 33.75	121 56.84
11	36 33.82	121 56.84
12	36 33.71	121 56.50
13	36 33.52	121 56.53
14	36 33.53	121 56.13
15	36 33.54	121 56.53
16	36 33.33	121 56.26
17	36 33.29	121 55.92
18	36 33.05	121 55.85
19	36 33.05	121 56.12

TABLE II (continued)

20	36° 32'.81	121° 55'.93
21	36 32.84	121 56.34
22	36 32.63	121 56.16
23	36 32.37	121 56.16
24	36 32.15	121 56.00
25	36 32.18	121 55.78
26	36 31.92	121 55.84
27	36 31.48	121 55.66
28	36 31.62	121 56.15
29	36 31.32	121 56.27
30	36 31.46	121 56.64
31	36 31.59	121 56.33
32	36 31.68	121 56.72
33	36 31.67	121 56.98
34	36 31.48	121 56.98
35	36 33.47	121 58.32
36	36 33.34	121 57.96
37	36 33.29	121 57.65
38	36 33.21	121 57.13
39	36 33.31	121 56.85
40	36 33.38	121 56.73
41	36 33.47	121 56.63
42	36 33.43	121 56.42

TABLE II (continued)

43	36° 33'.35	121° 56'.53
44	36 33.26	121 56.65
45	36 33.18	121 56.80
46	36 33.10	121 56.67
47	36 33.14	121 56.54
48	36 33.25	121 56.42
49	36 33.13	121 56.26
50	36 33.00	121 56.49
51	36 32.82	121 56.77
52	36 32.51	121 56.45
53	36 31.77	121 55.83
54	36 31.85	121 55.65
55	36 31.54	121 55.95

TABLE III

OBSERVED DATA

Station	Date Occupied	Hour (PST)	Depth (ft)	Observed gravity (mgal)
1	18 Aug 72	1045	99	979 905.38
2	"	1100	76	979 904.44
3	"	1135	65	979 904.56
4	"	1150	105	979 906.81
5	"	1215	83	979 905.38
6	"	1227	84	979 905.38
7	"	1240	106	979 906.13
8	"	1252	105	979 905.50
9	"	1300	112	979 905.31
10	"	1315	41	979 901.62
11	"	1325	34	979 901.38
12	"	1359	49	979 901.56
13	"	1410	62	979 902.38
14	"	1430	32	979 900.31
15	19 Aug 72	1238	58	979 902.06
16	"	1250	45	979 901.12
17	"	1303	26	979 899.38
18	"	1312	26	979 899.25
19	"	1320	44	979 900.75

TABLE III (continued)

20	19 Aug 72	1335	20	979 899.44
21	"	1352	70	979 903.38
22	"	1403	26	979 901.19
23	"	1425	92	979 904.44
24	"	1436	109	979 904.88
25	"	1442	44	979 901.38
26	"	1510	252	979 911.50
27	"	1550	35	979 900.44
28	"	1646	145	979 906.31
29	"	1715	69	979 903.56
30	"	1728	111	979 905.63
31	"	1740	145	979 907.00
32	"	1752	245	979 911.31
33	"	1833	202	979 909.87
34	"	1854	144	979 907.81
35	3 Oct 72	0810	155	979 907.81
36	"	0845	144	979 906.88
37	"	0900	161	979 907.50
38	"	0913	170	979 906.56
39	"	0925	118	979 904.25
40	"	0935	87	979 903.00
41	"	0944	73	979 902.06

TABLE III (continued)

42	3 Oct 72	0952	60	979 901.44
43	"	1001	71	979 901.94
44	"	1008	91	979 902.88
45	"	1019	133	979 904.19
46	"	1028	120	979 904.50
47	"	1039	89	979 902.88
48	"	1051	70	979 901.69
49	"	1102	50	979 900.75
50	"	1116	95	979 903.56
51	"	1127	145	979 906.06
52	"	1144	143	979 905.94
53	"	1202	120	979 903.44
54	"	1213	59	979 900.81
55	"	1228	99	979 903.00

III. REDUCTION OF DATA

The results of this survey are presented, as is usual, in the form of gravity anomalies. To obtain these anomalies corrections had to be applied to the measured gravity values and the corrected values compared with the computed theoretical value at each station.

A. THEORETICAL GRAVITY

For each station a value of theoretical gravity (THG) was computed for the reference spheroid. This is the value of gravity which would be expected if the earth were a perfectly uniform spheroid, fitted as closely as possible to mean sea level. The formula used is the internationally adopted standard (International Union of Geodesy and Geophysics, 1967):

$$THG = (978.03090+5.18552 \sin^2 L - 0.00570 \sin^2 2L) \text{ gal}$$

where L is the latitude of the station.

As most of the surveys are still based on the international gravity formula adopted in 1930 (International Association of Geodesy, Stockholm, 1930), this formula was also used so that the results could be directly compared with earlier work. The 1930 formula is:

$$THG = [978.0490(1+0.0052884 \sin^2 L - 0.0000059 \sin^2 2L] \text{ gal.}$$

B. EARTH TIDES

The earth is not an infinitely rigid body and responds to the

gravitational attractions of the sun and the moon. The deformations are accompanied by a gravity change of measurable magnitude. The measured gravity values were corrected for this change using tables furnished by the USGS.

C. INSTRUMENT DRIFT

The instrument drift was periodically checked by reoccupation of a base station in Monterey Bay and the measured gravity value corrected for the observed drift.

The measured gravity value at each station, after correction for earth tides and instrument drift, is considered to be the observed gravity (OG).

D. FREE AIR CORRECTION

The free air correction accounts for the fact that the gravity measurement is not made at mean sea level. Near the surface of the earth the gravity gradient is negative upwards and has a value of 0.09406 mgal/ft (Heiskanen, 1967). For underwater stations the correction (FAC) is:

$$FAC = (0.09406\ D_a)\ \text{mgal}$$

where $D_a = (D_o - TD)$ ft

in which D_o is the measured depth and TD is the tide height, both in feet. For land stations the correction is:

$$FAC = (0.09406 \times H)\ \text{mgal}$$

where H is the elevation in feet.

This correction is always negative for underwater stations and always positive for land stations.

E. BOUGUER CORRECTION

The Bouguer correction (BC) assumes that the distance between the station elevation and the reference elevation is filled with an infinite horizontal plate of rock material. For underwater stations it is applied in two parts. First, the effect of the attraction of a plate of water above the meter (BC1) is removed using the formula:

$$BC1 = 2\pi\rho_w G D_o$$

where ρ_w is the density of the water, G the universal gravitational constant and D_o the measured depth. Next, the volume is filled with a plate of rock using the correction (BC2):

$$BC2 = 2\pi\rho_r G D_a$$

where ρ_r is the density of the rock and D_a the depth below mean sea level as defined in the previous section.

Taking $\rho_w = 1.027$ gm/cm^3 and $\rho_r = 2.67$ gm/cm^3, the Bouguer correction is:

$$BC = (0.0131\ D_o + 0.0341\ D_a)\ \text{mgal}$$

for D_o and D_a in feet. This correction is positive.

For land stations we obtain (Heiskanen, 1967):

BC = (0.034 x H) mgal

where H is the elevation in feet. This correction is negative.

F. TERRAIN CORRECTION

The assumption of an infinite horizontal plate as in the Bouguer correction is not realistic. Valleys and hills around the station decrease the observed gravity value and must be compensated for. Theoretically the mass of each deviation from the Bouguer plate has to be calculated and its effect on the gravimeter computed. In practice the Hayford-Bowie templates and tables are used. For underwater stations the tables have to be modified to compensate for the presence of water in the "valleys" (air is assumed on the tables) and for the excess mass introduced by the Bouguer correction in the already rock-filled zones between the station depth and mean sea level.

Due to the irregularity of the bottom topography and the lack of detail of the hydrographic charts, the terrain correction (TC) is assumed to be accurate to only 0.5 mgal. This correction is always positive.

G. CURVATURE CORRECTION

The curvature correction (CC) is used to compensate for the assumption of a flat plate made in the Bouguer correction. This assumption is valid for short distances but must be corrected for greater distances. The formula used is:

$$CC = (0.0004462\ D_a - 3.282 \times 10^{-8} D_a^{\ 2} + 1.27 \times 10^{-15} D_a^{\ 3})\ \text{mgal}$$

This correction is negative.

H. COMPLETE PROCEDURE

To summarize, the complete procedure of data reduction was carried out as follows:

1) Theoretical gravity was computed by the formulas:

$$THG = (978.03090 + 5.18552\ \sin^2 L - 0.00570 \sin^2 2L)\ \text{gal} \qquad (1967)\ \text{and}$$

$$THG = [978.0490(1 + 0.0052884 \sin^2 L - 0.0000059 \sin^2 2L)]\ \text{gal} \qquad (1930)$$

2) Earth tide values were obtained from the tables and applied to the measured values.

3) Instrument drift was calculated and applied linearly as a function of time to the measured values.

4) A free air correction was applied using the formulas:

$$FAC = (0.09406\ D_a)\ \text{mgal}$$

for the underwater stations and:

$$FAC = (0.09406 \times H)\ \text{mgal}$$

for the land stations, to reduce the observed value to the reference spheroid.

5) In the case of the sea floor stations, the Bouguer correction was applied using the equation:

$$BC = (0.0131\ D_o + 0.0341\ D_a)\ \text{mgal}$$

to remove the effect of the water above the gravimeter and introduce an infinite horizontal plate of rock of density 2.67 g/cm^3. Figure 6 shows the plate of water removed, the plate of rock introduced and the resulting densities after the application of the Bouguer correction.

For the land stations the Bouguer correction was applied using the formula:

$$BC = (0.034 \times H)\ \text{mgal}.$$

6) The terrain correction was made by estimating the mean elevation of each compartment of the Hayford-Bowie templates and reading the correction from the tables. For the underwater stations the values of the tables were corrected as follows for the regions labeled in Figure 7:

Region 1 - value read from Hayford-Bowie table, added;

Region 2 - value read from Hayford-Bowie table multipled by [(2.67 - 1.03)/2.67], added, compensates for the presence of water instead of air;

Region 3 - value read from Hayford-Bowie table multiplied by [1 - (4.31 - 2.67)/2.67], subtracted, compensates for the excess mass introduced by the Bouguer correction.

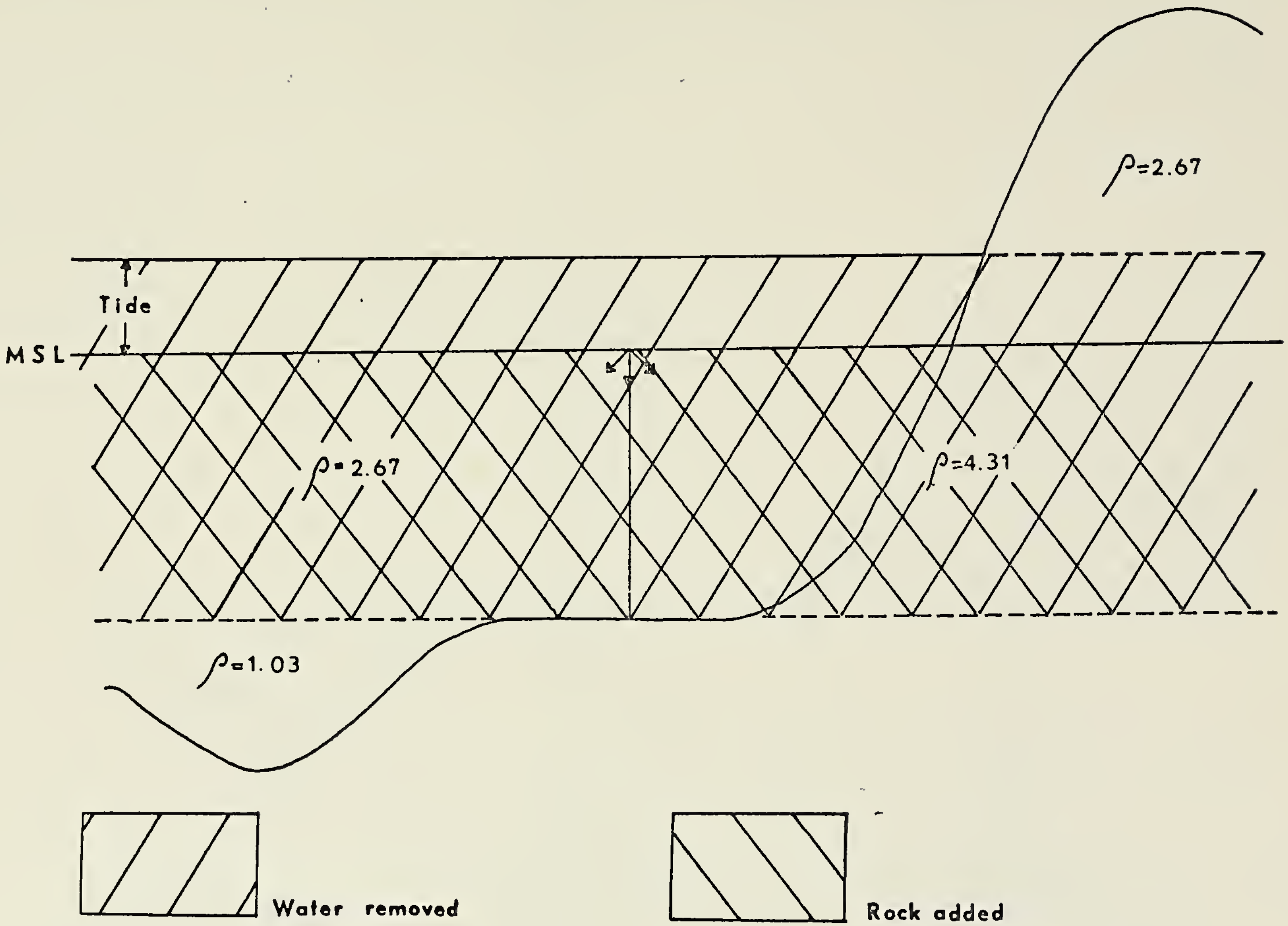

Figure 6. Bouguer Correction Applied and Resulting "Effective" Densities

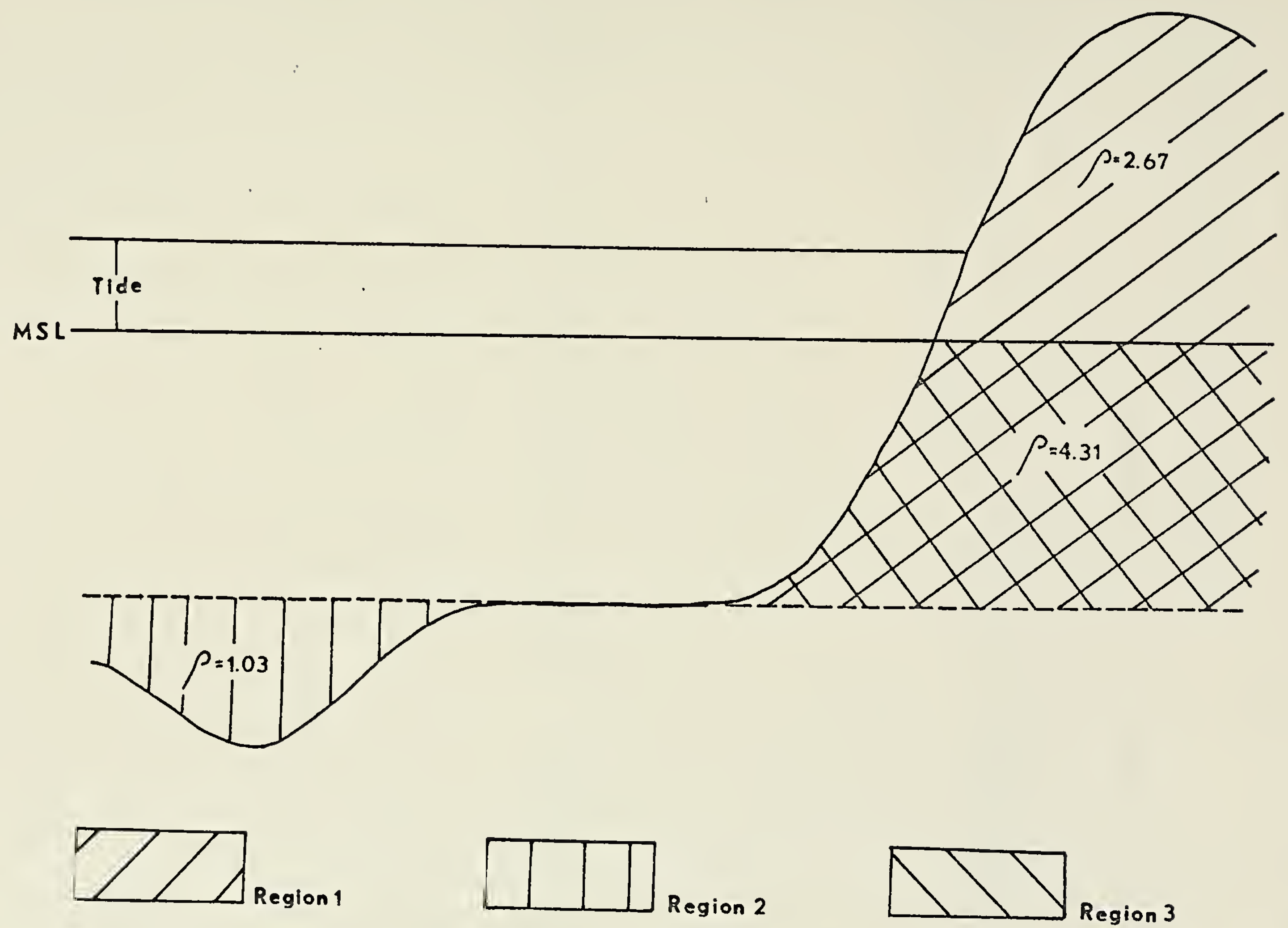

Figure 7. Terrain Correction Schematic

7) Curvature correction applied using the formula:

$$CC = (0.0004462\ D_a - 3.282 \times 10^{-8} D_a^{\ 2} + 1.27 \times 10^{-15} D_a^{\ 3})\ \text{mgal}$$

to compensate for the curvature of the earth.

Table IV lists the theoretical gravity values computed for each station using the 1930 and 1967 formulas and Table V lists the corrections applied to each sea-floor station. The theoretical gravity values for the land stations are listed in Table I.

TABLE IV

THEORETICAL GRAVITY

Station	1930 formula (mgal)	1967 formula (mgal)
1	979 878.91	979 865.42
2	979 879.02	979 865.54
3	979 879.54	979 866.05
4	979 879.67	979 866.18
5	979 879.37	979 865.88
6	979 879.20	979 865.71
7	979 878.97	979 865.48
8	979 878.68	979 865.19
9	979 878.71	979 865.22
10	979 879.15	979 865.66
11	979 879.25	979 865.76
12	979 879.10	979 865.61
13	979 878.82	979 865.33
14	979 878.84	979 865.35
15	979 878.85	979 865.36
16	979 878.55	979 865.06
17	979 878.49	979 865.00
18	979 878.15	979 864.66
19	979 878.15	979 864.66

TABLE IV (continued)

20	979 877.80	979 864.31
21	979 877.84	979 864.35
22	979 877.54	979 864.05
23	979 877.17	979 863.68
24	979 876.85	979 863.36
25	979 876.90	979 863.41
26	979 876.52	979 863.03
27	979 875.89	979 862.39
28	979 876.09	979 862.59
29	979 875.66	979 862.16
30	979 875.86	979 862.36
31	979 876.05	979 862.55
32	979 876.18	979 862.68
33	979 876.17	979 862.67
34	979 875.89	979 862.39
35	979 878.75	979 865.26
36	979 878.56	979 865.07
37	979 878.49	979 865.00
38	979 878.38	979 864.89
39	979 878.52	979 865.03
40	979 878.62	979 865.13
41	979 878.75	979 865.26

TABLE IV (continued)

42	979 878.69	979 865.20
43	979 878.58	979 865.09
44	979 878.45	979 864.96
45	979 878.33	979 864.84
46	979 878.22	979 864.73
47	979 878.28	979 864.79
48	979 878.43	979 864.94
49	979 878.26	979 864.77
50	979 878.07	979 864.58
51	979 877.82	979 864.32
52	979 877.37	979 863.88
53	979 876.31	979 862.81
54	979 876.42	979 862.93
55	979 875.98	979 862.48

TABLE V

GRAVITY CORRECTIONS

Station	FAC (mgal)	BC (mgal)	TC (mgal)	CC (mgal)
1	9.28	4.66	4.29	0.05
2	7.12	3.58	4.19	0.04
3	6.07	3.05	4.62	0.03
4	9.83	4.94	4.56	0.05
5	7.75	3.90	4.33	0.03
6	7.84	3.94	4.20	0.04
7	9.90	4.98	4.18	0.05
8	9.80	4.93	4.38	0.05
9	10.45	5.26	4.07	0.05
10	3.76	1.90	3.91	0.02
11	3.09	1.57	3.93	0.01
12	4.50	2.27	3.94	0.02
13	5.71	2.88	3.92	0.03
14	2.88	1.46	4.01	0.01
15	5.44	2.73	3.91	0.03
16	4.20	2.11	3.97	0.02
17	2.42	1.22	3.97	0.01
18	2.41	1.21	3.95	0.01
19	4.10	2.06	3.87	0.02

TABLE V (continued)

20	1.48	0.93	3.90	0.01
21	6.54	3.29	4.21	0.04
22	2.39	1.21	4.06	0.01
23	8.59	4.32	4.22	0.04
24	10.18	5.12	4.52	0.04
25	4.06	2.05	4.14	0.02
26	23.61	11.86	5.01	0.09
27	3.16	1.60	4.72	0.02
28	13.47	6.78	5.13	0.06
29	6.30	3.19	4.68	0.03
30	10.24	5.17	5.14	0.04
31	13.43	6.77	4.68	0.06
32	22.84	11.49	5.53	0.09
33	18.78	9.46	5.74	0.08
34	13.33	6.72	5.64	0.06
35	14.39	7.25	4.46	0.06
36	13.37	6.73	4.83	0.06
37	14.97	7.54	4.58	0.07
38	15.83	7.97	4.48	0.07
39	10.95	5.52	4.05	0.04
40	8.04	4.06	3.96	0.03
41	6.73	3.40	4.02	0.03

TABLE V (continued:

42	5.52	2.79	4.02	0.03
43	6.57	3.31	3.98	0.03
44	8.46	4.26	4.00	0.03
45	12.42	6.24	4.33	0.06
46	11.20	5.63	3.99	0.06
47	8.30	4.17	3.94	0.04
48	6.53	3.28	3.97	0.03
49	4.66	2.34	3.89	0.02
50	8.91	4.47	3.93	0.04
51	13.62	6.84	4.45	0.06
52	13.47	6.76	4.58	0.06
53	11.32	5.68	5.28	0.05
54	5.61	2.81	4.61	0.02
55	9.39	4.70	5.02	0.05

IV. GRAVITY ANOMALIES

A gravity anomaly is the difference between the corrected observed gravity and the computed theoretical value. In general, several different anomalies are considered depending on the corrections applied to the observed data.

A. FREE AIR ANOMALY

The free air anomaly (FAA) is the gravity value after the free air correction is applied:

$$FAA = (OG + FAC - THG) \text{ mgal.}$$

Figure 8 shows the free air anomaly chart for Carmel Bay using the 1930 formula for the theoretical gravity.

B. SIMPLE BOUGUER ANOMALY

The simple Bouguer anomaly (SBA) is the gravity value when the free air correction and the Bouguer correction have been applied:

$$SBA = (OG + FAC + BC - THG) \text{ mgal}$$

or

$$SBA = (FAA + BC) \text{ mgal.}$$

Figure 9 shows the resulting simple Bouguer anomaly chart obtained, again using the 1930 formula for the theoretical gravity.

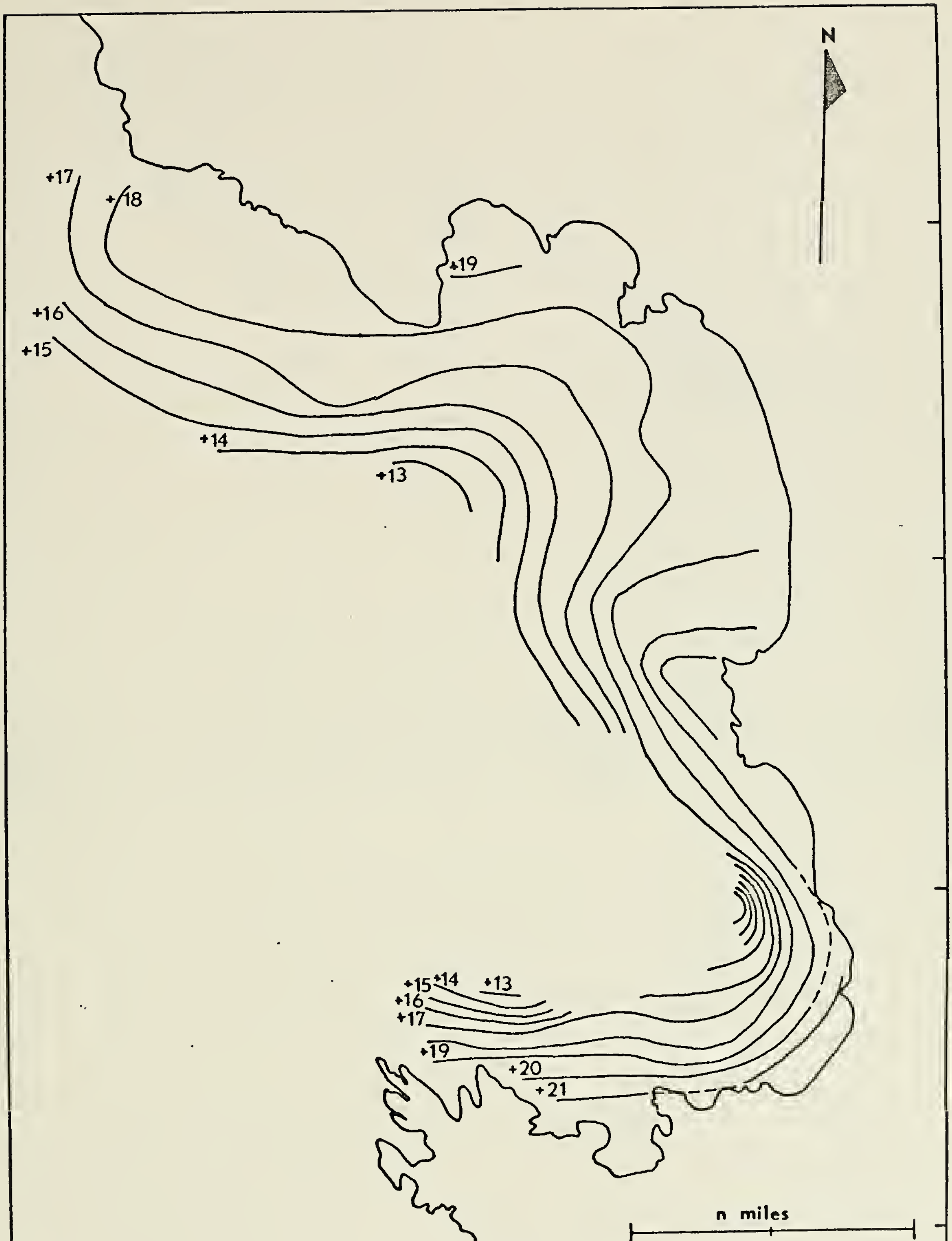

Figure 8. Free Air Anomaly Map of Carmel Bay Based on the 1930 Formula for Theoretical Gravity

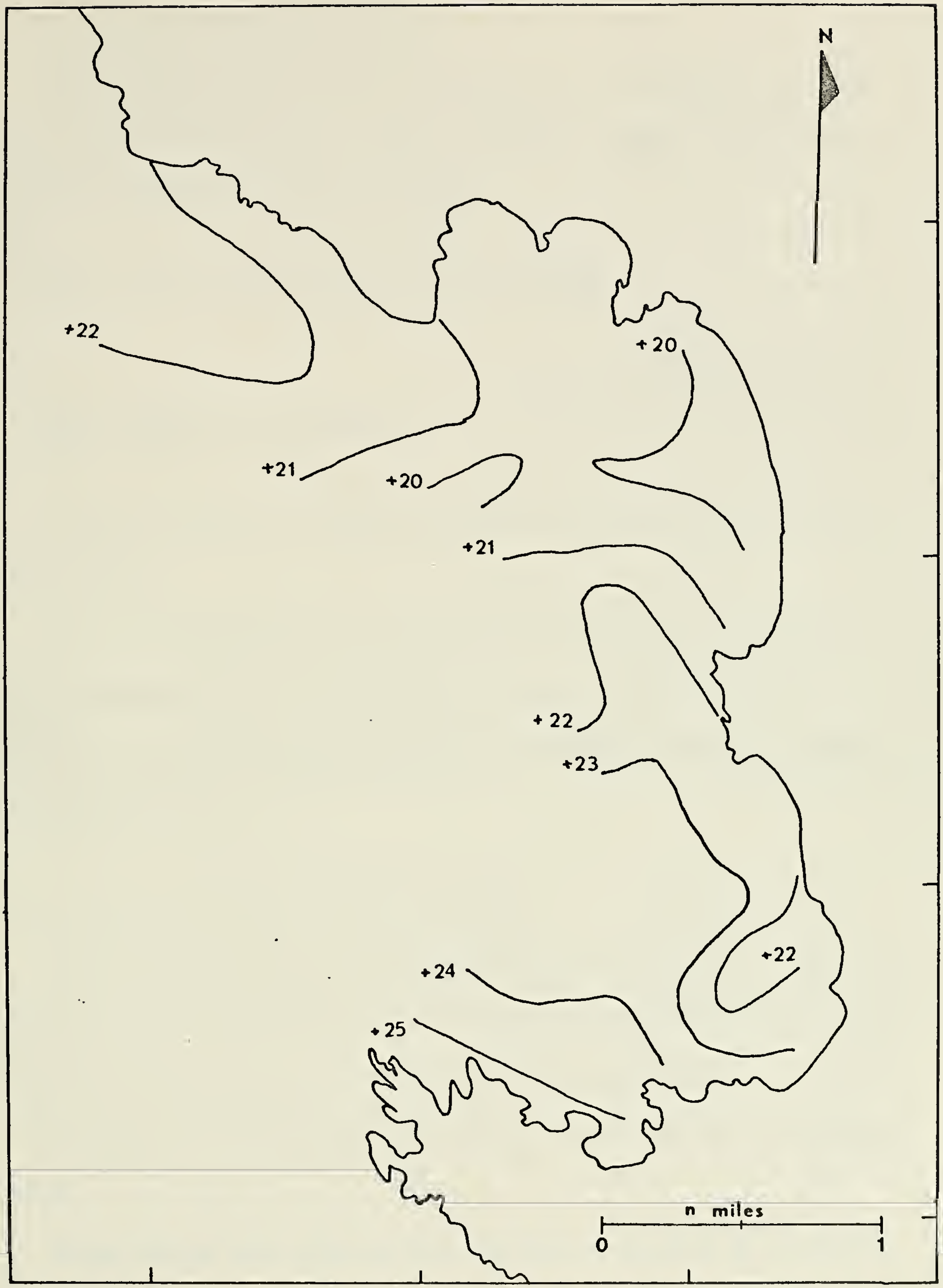

Figure 9. Simple Bouguer Anomaly Map of Carmel Bay Based on the 1930 Formula for Theoretical Gravity

C. COMPLETE BOUGUER ANOMALY

The complete Bouguer anomaly (CBA) is the anomaly which results after the free air correction, Bouguer correction, terrain correction and curvature correction have been applied:

$$CBA = (OG + FAC + BC + TC - CC - THG) \text{ mgal}$$

or

$$CBA = (SBA + TC - CC) \text{ mgal.}$$

Figure 10 shows the complete Bouguer anomaly chart based on the 1930 formula.

Table VI summarizes the above gravity anomalies for each station. In a similar fashion Table VII shows the gravity anomalies based on the 1967 formula for the theoretical gravity. The CBA for the land stations are shown in Table 1.

D. MASS COMPENSATED FREE AIR CHART

Figure 11 shows the approximate differences that would be expected between the theoretical gravity values and the values observed by a sea-surface gravity meter and corrected for Eötvös and ship motion, based on the 1930 gravity formula, called the mass compensated free air values (MCV).

These values were obtained from the free air anomaly by correcting for the double Bouguer effect of the water. Thus:

$$MCV = [FAA + (0.262\ D_a)]\ \text{mgal}$$

where D_a, as defined before, is in feet.

This figure is included so that a future sea-surface gravity survey of the bay can be directly compared with the results reported herein.

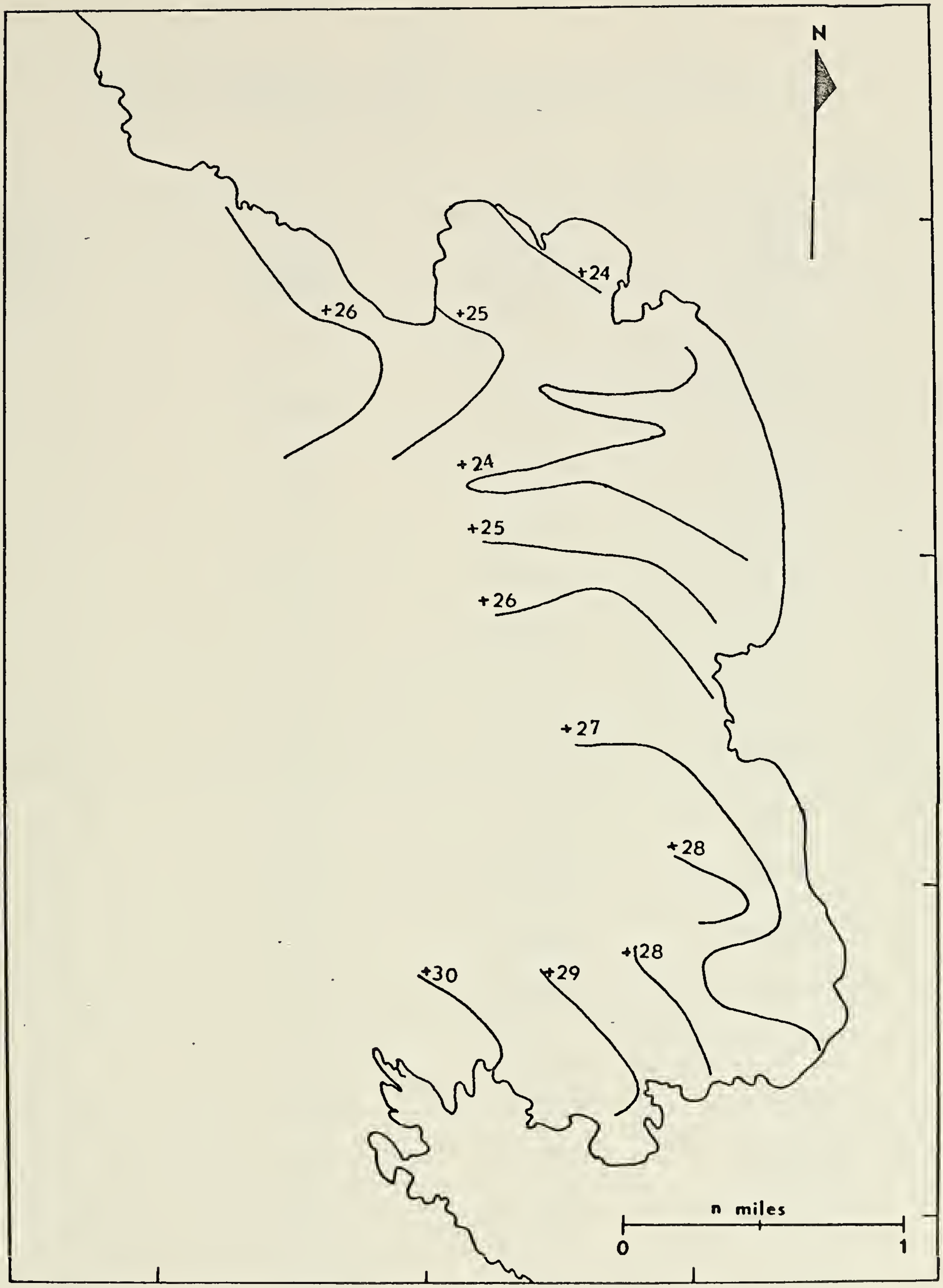

Figure 10. Complete Bouguer Anomaly Map of Carmel Bay Based on the 1930 Formula for Theoretical Gravity

TABLE VI

GRAVITY ANOMALIES BASED ON THE 1930 FORMULA FOR THEORETICAL GRAVITY

Station	FAA (mgal)	SBA (mgal)	CBA (mgal)
1	17.15	21.82	26.06
2	18.29	21.87	26.02
3	18.90	21.95	26.54
4	17.27	22.21	26.72
5	18.26	22.15	26.45
6	18.30	22.25	26.41
7	17.22	22.20	26.33
8	17.01	21.94	26.27
9	16.11	21.36	25.38
10	18.66	20.56	24.45
11	19.00	20.56	24.48
12	17.97	20.24	24.16
13	17.80	20.69	24.58
14	18.60	20.06	24.06
15	17.77	20.51	24.39
16	18.33	20.44	24.39
17	18.45	19.66	23.62
18	18.67	19.88	23.82

TABLE VI (continued)

19	18.48	20.54	24.39
20	19.76	20.69	24.58
21	18.97	22.26	26.43
22	21.21	22.41	26.46
23	18.64	22.96	27.14
24	17.84	22.95	27.43
25	20.42	22.47	26.59
26	11.35	23.21	28.13
27	21.36	22.97	27.67
28	16.72	23.50	28.57
29	21.59	24.78	29.43
30	19.51	24.68	29.78
31	17.52	24.28	28.90
32	12.26	23.75	29.19
33	14.90	24.36	30.02
34	18.55	25.27	30.85
35	14.63	21.87	26.27
36	14.94	21.67	26.44
37	14.01	21.55	26.06
38	12.31	20.28	24.69
39	14.73	20.24	24.25
40	16.32	20.37	24.30

TABLE VI (continued

41	16.56	19.96	23.95
42	17.18	19.97	23.96
43	16.80	20.11	24.06
44	15.93	20.18	24.15
45	13.42	19.66	23.93
46	15.03	20.67	24.60
47	16.29	20.46	24.36
48	16.69	19.97	23.91
49	17.80	20.14	24.01
50	16.55	21.02	24.91
51	14.62	21.46	25.85
52	15.07	21.82	26.34
53	15.76	21.43	26.66
54	18.77	21.57	26.16
55	17.59	22.29	27.26

TABLE VII

GRAVITY ANOMALIES BASED ON THE 1967 FORMULA FOR THEORETICAL GRAVITY

Station	FAA (mgal)	SBA (mgal)	CBA (mgal)
1	30.64	35.31	39.55
2	31.78	35.35	39.51
3	32.38	35.43	40.03
4	30.75	35.69	40.21
5	31.74	35.64	39.94
6	31.79	35.73	39.90
7	30.71	35.69	39.82
8	30.50	35.43	39.76
9	29.59	34.85	38.87
10	32.15	34.05	37.94
11	32.48	34.05	37.97
12	31.46	33.73	37.65
13	31.29	34.17	38.07
14	32.09	33.55	37.55
15	31.26	33.99	37.88
16	31.82	33.93	37.88
17	31.94	33.15	37.11
18	32.16	33.37	37.31
19	31.97	34.03	36.88

TABLE VII (continued)

20	33.25	34.18	38.07
21	32.46	35.75	39.93
22	34.70	35.91	39.96
23	32.14	36.46	40.64
24	31.33	36.45	40.92
25	33.91	35.96	40.08
26	24.85	36.71	41.62
27	34.86	36.46	41.17
28	30.22	37.00	42.07
29	35.09	38.28	42.93
30	33.01	38.18	43.27
31	31.01	37.78	42.40
32	25.76	37.25	42.68
33	28.40	37.85	43.51
34	32.04	38.76	44.34
35	28.11	35.36	39.76
36	28.43	35.16	39.93
37	27.50	35.04	39.55
38	25.80	33.77	38.18
39	28.22	33.73	37.73
40	29.81	33.86	37.78
41	30.05	33.45	37.44

TABLE VII (continued)

42	30.67	33.46	37.45
43	30.29	33.60	37.55
44	29.42	33.67	37.64
45	26.91	33.15	37.42
46	28.52	34.16	38.09
47	29.78	33.95	37.85
48	30.18	33.47	37.40
49	31.29	33.63	37.50
50	30.04	34.51	38.40
51	28.11	34.95	39.34
52	28.56	35.32	39.84
53	29.25	34.93	40.16
54	32.26	35.07	39.65
55	31.08	35.78	40.76

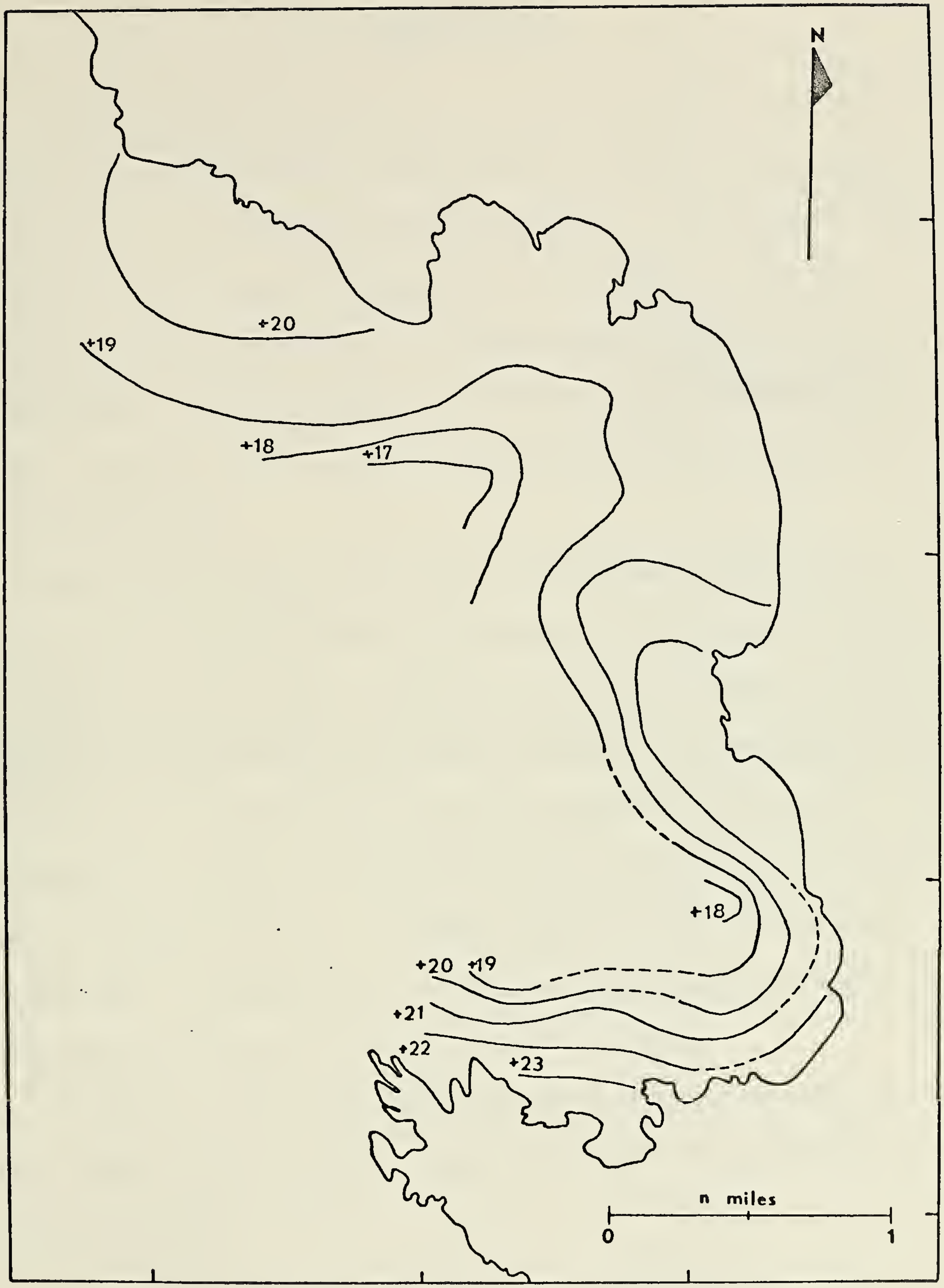

Figure 11. Mass Compensated Free Air Chart of Carmel Bay Based on the 1930 Formula for Theoretical Gravity

V. INTERPRETATION

The interpretation of gravity data is not an easy process. Gravity contours usually do not relate directly to structure contours and attempting to do so may result in highly erroneous interpretaion. Gravity data is not unique; by itself it is not a reliable source of information for the interpretation of subsurface geology. The more available data there is from other sources, the more specific can be the interpretation of the gravity data. It can be said that the interpretation of gravity data of itself is a speculative process.

This assuredly is the case with the interpretation resulting from the present study. Information from other sources on the subsurface structure of Carmel Bay is very scarce. Simpson (1972) conducted seismic reflection profiling in the bay with a 3.5 kHz high resolution profiler and a 300 J sparker, but in the shallow regions the high reflectivity of the sand sediments and the lack of resolution in the first 6 fathoms of the records due to the sparker pulse and air bubbles masked any layering that might be expected. In consequence, the interpretation presented here can be considered to be done on the basis of gravity data alone.

Figure 12 is a chart showing the interpolated and extrapolated complete Bouguer anomaly contours. The land gravity trends are based on work by Sieck (1961).

The two most evident features are the low anomaly between Pescadero Point and Abalone Point extending seaward in the direction of

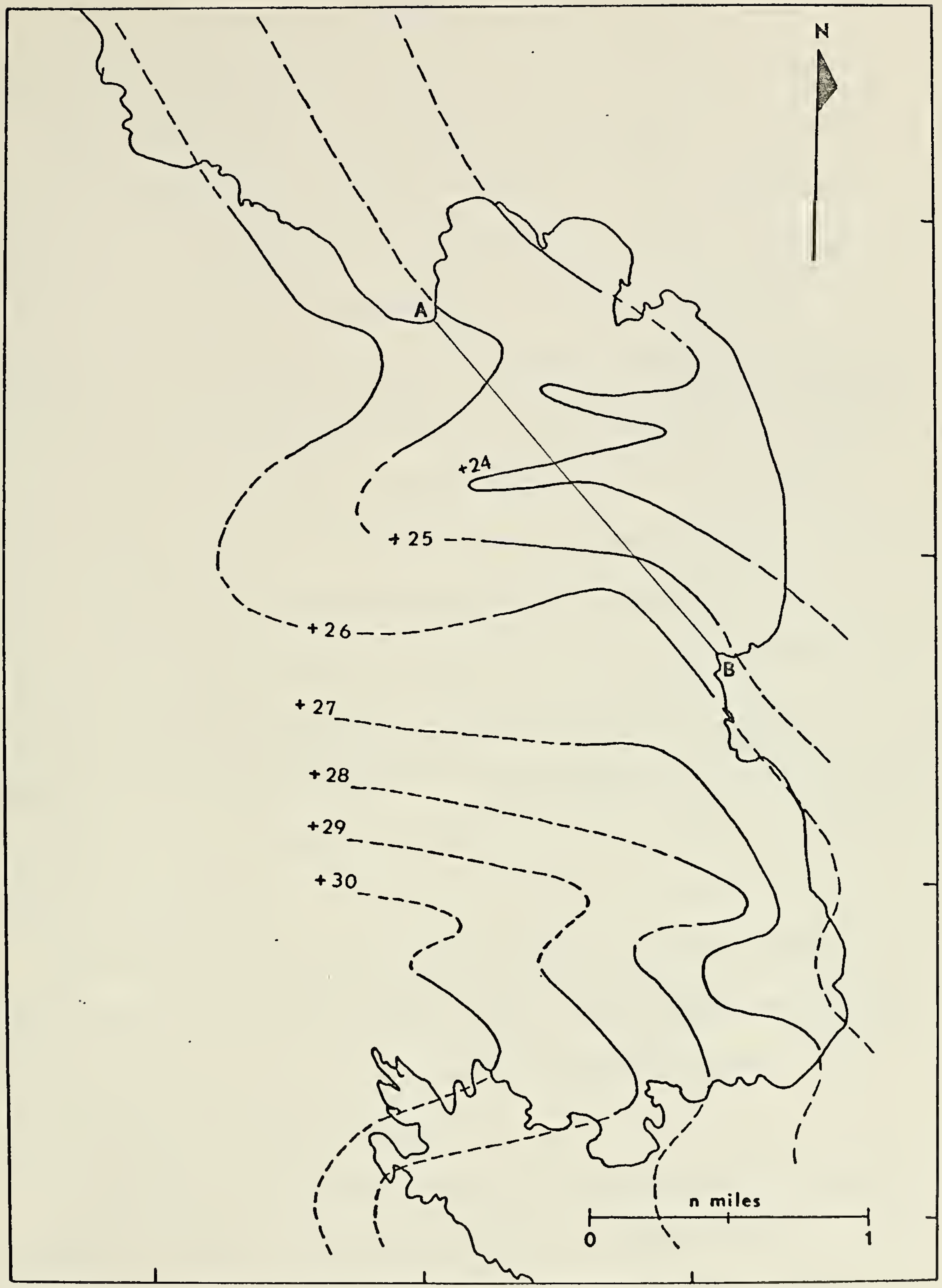

Figure 12. Complete Bouguer Anomaly Chart of Carmel Bay Including Extrapolations of Contours

the secondary canyon, and the bending of the anomaly lines in the southern part of the bay in the region of the Carmel Submarine Canyon.

Figure 13 is a profile of the complete Bouguer gravity anomaly from Pescadero Point to Abalone Point (A-B on Figure 12). The difference of 1.5 mgal cannot be attributed to the presence of the Carmelo Formation inshore of the profile nor to the thin layer of sediments indicated by Simpson (1972). As mentioned before, the seismic work done in the area does not show any sedimentary rock layer, but the granodiorite basement shown in the geological map of Carmel Bay (Figure 2) is not compatible with the gravity profile. A more plausible explanation results if the profile is considered to be due to an erosional and depositional feature. It is possible that the Pleistocene glaciers might have cut the secondary canyon in the bay and sediments, probably derived from erosion of granodiorite and Carmelo Formation, filled the canyon. The thickness of the sediments is estimated to be over 500 m. Future work is needed to check this hypothesis.

No evidence was found for the fault between Pescadero Point and Abalone Point as proposed by Bowen (1965), but this fault, laying parallel to the regional trend of the area, could be masked by the effect of the layer of sediments proposed above.

The bending of the anomaly lines in the southern part of the bay is believed to be due to faulting along the Carmel Submarine Canyon. This fault could be the seaward continuation of the one proposed by Simpson (1972), running down the San Jose Creek Valley (Figure 2).

It is evident that the submarine geology of Carmel Bay is not yet well known and much more work needs to be done before it can be well understood.

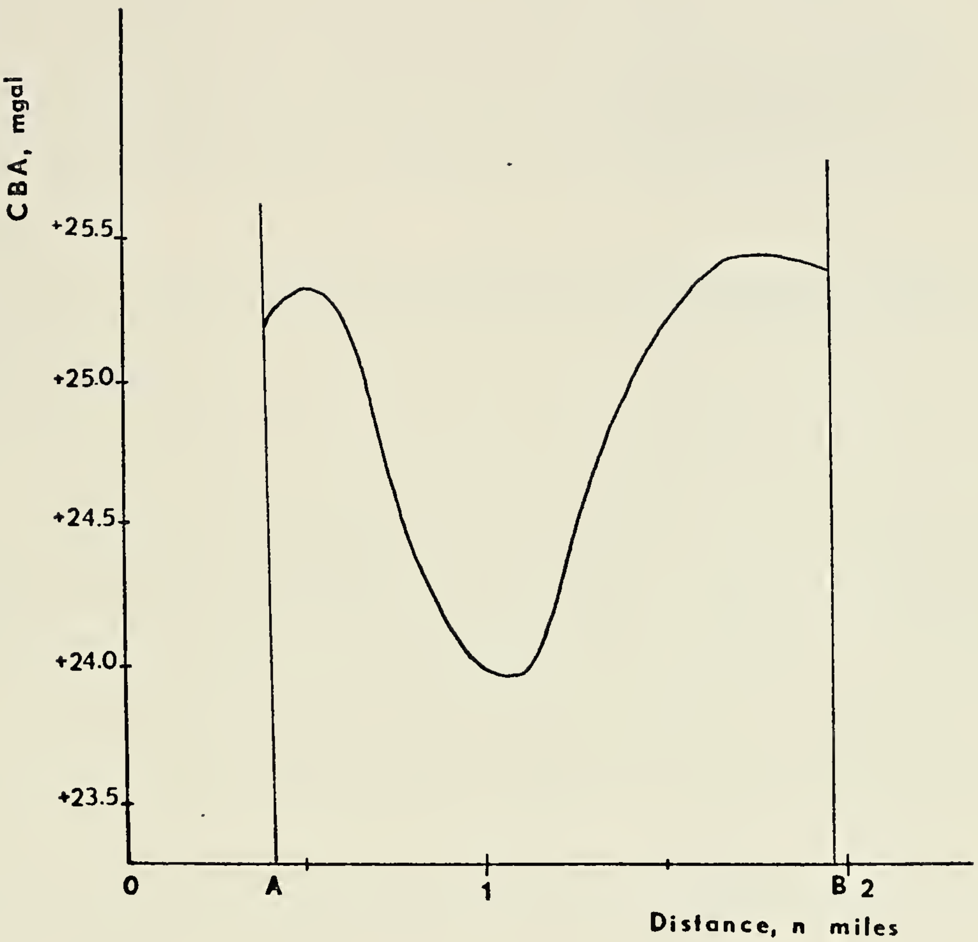

Figure 13. Complete Bouguer Gravity Profile from Pescadero Point (A) to Abalone Point (B), Carmel Bay

VI. SUGGESTIONS FOR FURTHER STUDIES

Further studies that would help to define the marine geology of Carmel Bay should include:

1. magnetic measurements in the bay;
2. seismic refraction and reflection measurements in the bay;
3. carbon, carbonate and organic nitrogen analysis of sediments;
4. current and water column structure determinations within the bay, and
5. periodic surveys of the Carmel Submarine Canyon with a narrow beam profiler.

BIBLIOGRAPHY

Bomford, B. G. 1962. Geodesy. 2d ed. Oxford University Press.

Bowen, O. E. 1965. Point Lobos, a Geological Guide. California Division of Mines and Geology Mineral Information Service. 18(4).

Dobrin, M. B. 1960. Introduction to Geophysical Prospecting. 2d ed. McGraw-Hill Book Company.

Grant, F. S., and G. F. West. 1965. Interpretation Theory in Applied Geophysics. McGraw-Hill Book Company.

Griffiths, D. H., and R. F. King. 1965. Applied Geophysics for Engineers and Geologists. Pergamon Press.

Heiskanen, W. A., and F. A. Vening Meinesz, 1958. The Earth and Its Gravity Field. McGraw-Hill Book Company.

Heiskanen, W. A. and H. Moritz, 1967. Physical Geodesy. W. H. Freeman and Company.

Lawson, A. C. 1893. The Geology of Carmelo Bay. Bull. Dept. Geol., University of California, Berkeley 1:1-59.

Martin, B. D. 1964. Monterey Submarine Canyon, California: Genesis and Relationship to Continental Geology. PhD Dissertation, University of Southern California, Los Angeles. (Unpublished Report).

Martin, B. D., and K. O. Emery. 1967. Geology of Monterey Canyon, California. Bull. Amer. Assoc. Petrol. Geologists. 51(11):2281-2304.

Nili-Esfahani, A. 1965. Investigation of Paleocene Strata, Point Lobos, Monterey County, California. M. A. Thesis, University of California, Los Angeles. (Unpublished Report).

Shepard, R. P., and R. F. Dill. 1966. Submarine Canyons and Other Sea Valleys. Rand McNalley & Co., Chicago.

Shepard, R. P., and K. O. Emery. 1941. Submarine Topography Off the California Coast: Canyons and Tectonic Interpretation. Geological Soc. Amer. Spec. Paper 31.

Sieck, H. C. 1961. A Gravity Investigation of the Monterey-Salinas Area. University of California. (Unpublished Report).

Simpson, J. P. 1972. The Geology of Carmel Bay, California. M. S. Thesis. Naval Postgraduate School, Monterey. (Unpublished Report).

Trask, J. B. 1854. Report of the Geology of the Coast Mountains and Particularly of the Sierra Nevada. Assembly Journal, Appendix Doc. 9, 5th Session, State Legislature, Calif. 21, 22, 36.

Trask, J. B. 1855. Report of the Geology of the Coast Mountains. Assembly Journal, Appendix Doc. 14, 6th Session, State Legislature, Calif. 28.

Zardeskas, R. A. 1971. A Bathymetric Chart of Carmel Bay, California. M. S. Thesis, Naval Postgraduate School, Monterey, California. (Unpublished Report).

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3. ABSTRACT

Bottom gravity data was obtained on 55 stations down to the 50 fathoms depth contour to produce the first gravity anomaly charts of Carmel Bay. The techniques of data collection and reduction are discussed. No evidence was found for the fault between Pescadero Point and Abalone Point proposed by Bowen. A layer of sediments over 500 meters thick, probably of the Paleocene Carmelo series, is indicated extending seaward from Carmel Beach, partially filling the secondary canyon. A new fault is proposed along the axis of the Carmel submarine canyon.

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
CARMEL BAY						
GEOLOGY						
GEOPHYSICS						
GRAVITY						
MARINE GEOLOGY						

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